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Theoretical study on axial capacity of CFRP reinforced self-stressing concrete filled steel tubes

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Abstract. Since the expansion of the cement during curing was constraint by the steel tube, the concrete core in the self-stressing concrete-filled steel tubes (SSCFST) is under tri-axially compression before applying load, which increases the axial capacity of the SSCFST. In addition, Carbon fiber reinforced polymer (CFRP) wrapping can avoid bucking of the steel tube, increase the axial capacity and improve the durability of SSCFST. This study presents a theoretical study on axial capacity of the SSCFST wrapped with CFRP sheets. Several basic assumptions are proposed. The ultimate equilibrium method was employed to analyze the axial capacity, of which two limit states, including steel tube bucking and CFRP sheets rupturing were considered. The analytical results from an example show that the initial self-stress improves axial capacity of the SSCFST by about 30% and the CFRP reinforcement improves axial capacity by about 15%.

Introduction

Concrete filled steel tube (CFST) column has made significant advances in building and bridge applications due to its high strength, high stiffness and high ductility for full usage of construction materials [1,2]. To keep the concrete core under tri-axially compression before applying load and avoid the premature bulking of the steel tube, Self-stressing concrete and CFRP sheets are employed in CFST. The self-stressing concrete-filled steel tubes (SSCFST) have higher axial capacity than CFST. A number of experimental studies [3-6] on SSCFST have been conducted in recent years and the mechanical performances and design theory [6] have been proposed.

In Civil Engineering, Carbon Fiber Reinforced Polymers (CFRP) has mainly been used to repair and to upgrade reinforced existing structures. CFRP externally wrapping on CFST can avoid bucking of the steel tube, increase the axial capacity and improve the durability. Static performances and hysteretic behavior of this structural component were proposed [7]. Some experimental studies [8-11] on FRP wrapping CFST columns are conducted and an analytical model to predict the behavior of the composite columns under axial loading was developed.

The axial capacity and durability of the SSCFST can be improved by wrapping CFRP as well. This paper presents a simple close-form solution for obtaining the axial capacity of SSCFST reinforced with CFRP, as shown in Fig. 1. An example is employed to verify the effects of the initial self-stress of the concrete and the reinforcement of the CFRP sheet.

Basic assumptions

The following assumptions are made in this analytical study:

(1) The interfaces between the concrete and the steel tube and between the steel tube and the CFRP sheet are constrained.
(2) The radial stress in the steel tube is ignored and the steel tube is under biaxial stress.
(3) The CFRP material is linear elastic.
(4) Only the circumferential stress in the CFRP sheet, i.e. the stress along the fiber direction is considered and the radial stress and the longitudinal stress are ignored.

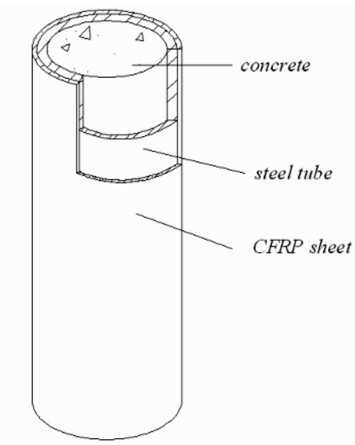


Fig. 1 Schematic of SSCFST

Axial capacity

The circumferential stress in the steel tube caused by expansion of the self-stressing concrete can be expressed as $\varepsilon_s(t) = a_f \mathrm{A}(\alpha)(1 - e^{-b_f \cdot B(\alpha)t})$, the initial circumferential self-stress σ_{ss} can be calculated in accordance with the force balance of the steel tube, where a_f, b_f ,$A(\alpha)$ and $B(\alpha)$ can be deserved from a regression formula [6]. Since the concrete in the steel tube is under tri-axial compression. The axial compressive strength of the concrete σ_l can be expressed as [12]:

$$\sigma_l = f_{ck} + k\sigma_r \tag{1}$$

where f_{ck} is the standard compressive strength of the concrete, σ_l the lateral pressure of the concrete, k the lateral pressure coefficient. k is normally between 3 to 5 in accordance with the experimental results [12] and assumed to be 4 in this study. Considering both the self-stressing and axial compression, σ_r can be expressed as:

$$\sigma_r = \sigma_{cr} + \sigma_{ss} \tag{2}$$

where σ_r is the lateral pressure of the concrete core caused by axial compression.

The circumferential stress σ_{ft} in the CFRP can be expressed as:

$$\sigma_{ft} = E_f \varepsilon_{ft} \tag{3}$$

where ε_{ft} and E_f are the circumferential strain and the Young's modulus of the CFRP sheet, respectively.

The critical state of the steel tube is analyzed using the maximum shear stress theory, known as the Tresca yield criterion. It can be expressed as:

$$\sigma_{st} - \sigma_{sl} + \sigma'_{st} = f_y \tag{4}$$

where σ_{st} and σ_{sl} are the circumferential tensile stress and the axial compressive stress of the steel tube, respectively, σ_{st}' the circumferential tensile stress of steel tube that caused by self-stressing and f_y the yield strength of the steel tube.

Fig.2 shows the stress distribution in SSCFST under axial compression. The lateral pressure of the concrete σ_{cr} and the radial stress of the CFRP σ_{fr} can be obtained from the following equations:

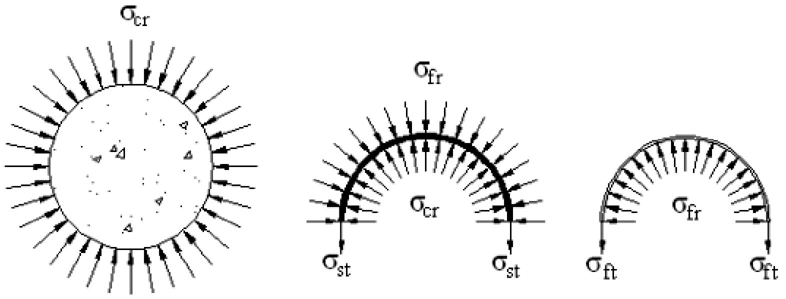
$$\sigma_{cr} = \sigma_{fr} + \frac{t_s}{r}\sigma_{st} \tag{5}$$

$$\sigma_{fr} = \frac{t_s}{r}\sigma_{ft} \tag{6}$$

The initial circumferential self-stress σ_{ss} and the circumferential stress of the steel tube σ_{st}' has the following relationship:

$$\sigma_{ss} = \frac{t_s}{r}\sigma'_{st} \tag{7}$$

where t_f and t_s are the thickness of the CFRP sheet and the steel tube, respectively, and r the inner diameter of the steel tube.



concrete ***steel tube*** ***CFRP***

Fig. 2 Stress distribution in SSCFST

The cross section area of the concrete, the steel tube and the CFRP are A_c, A_s and A_f, respectively. Approximately, $A_s = 2\pi r t_s$, $A_f = 2\pi r t_f$, $A_c = \pi r^2$.

So, $\frac{t_s}{r} = \frac{A_s}{2A_c}$, $\frac{t_f}{r} = \frac{A_f}{2A_c}$

Therefore, Eqs. (5) (6) (7) can be rewritten as:

$$\sigma_{cr} = \sigma_{fr} + \frac{A_s}{2A_c}\sigma_{st} \tag{8}$$

$$\sigma_{fr} = \frac{A_f}{2A_c}\sigma_{ft} \tag{9}$$

$$\sigma_{ss} = \frac{A_s}{2A_c}\sigma'_{st} \tag{10}$$

Substituting Eq. (9) into Eq. (8), the lateral pressure σ_{cr} can be written as:

$$\sigma_{cr} = \sigma_{ft}\frac{A_f}{2A_c} + \sigma_{st}\frac{A_s}{2A_c} \tag{11}$$

According to Hooke's law,

$$\varepsilon_{st} = \frac{1}{\mathrm{E}_s}(\sigma_{st} - \upsilon_s\sigma_{sl}) \tag{12}$$

where μ_s and E_f are the Poisson's ratio and Young's modulus of the steel tube, respectively, ε_{st} the circumferential strain of the steel tube.

Substituting Eq. (4) into Eq. (12) gives the circumferential strain of the steel tube ε_{st}, which can be rewritten as:

$$\varepsilon_{st} = \frac{1}{\mathrm{E}_s}[(1-\upsilon_s)\sigma_{st} - \upsilon_s\sigma'_{st} + \upsilon_s f_y] \tag{13}$$

According to the basis assumption (1), the circumferential strain of the steel tube equals to the circumferential strain of the CFRP. Substituting Eq. (13) into Eq. (3) can obtain the circumferential stress in the CFRP as:

$$\sigma_{ft} = \frac{\mathrm{E}_f}{\mathrm{E}_s}\left[(1-\upsilon_s)\sigma_{st} - \upsilon_s\sigma'_{st} + \upsilon_s f_y\right] \tag{14}$$

Substituting Eq. (14) into Eq. (9) gives the circumferential tensile stress of the CFRP sheet:

$$\sigma_{fr} = \frac{E_f A_f}{2E_s A_c}\left[(1-\mu_s)\sigma_{st} - \mu_s\sigma'_{st} + \mu_s f_y\right] \tag{15}$$

The first limit state of CFRP-SSCFST is steel tube bucking. The axial capacity of the CFRP-SSCFST can be described as:

$$N_{u1} = A_c\sigma_l + A_s\sigma_{sl} \tag{16}$$

Substituting Eqs. (2) (4) (10) (11) (14) into Eq. (16) gives axial capacity as:

$$N_{u1} = A_c f_{ck}\left[1+\alpha\frac{\sigma_{st}}{f_y}+\beta\frac{\sigma_{ss}}{f_{ck}}+\gamma\right] \tag{17}$$

where

$$\alpha = 3\xi_s + \frac{2E_f A_f f_y}{E_s A_c f_{ck}}(1-\mu_s)$$

$$\beta = 6 - \frac{4E_f A_f}{E_s A_s}\mu_s$$

$$\gamma = \frac{2E_f A_f f_y}{E_s A_c f_{ck}}\mu_s - \xi_s$$

$$\xi_s = \frac{\mathrm{A}_s f_y}{\mathrm{A}_c f_{ck}}$$

ξ_s is defined as the coefficient of the constraint effect caused by the steel tube. The circumferential tensile stress of the steel tube σ_{st} will be the yield stress f_y when the steel tube yields. Therefore, Equation (17) can be simplified as:

$$N_{u1} = A_c f_{ck}\left[1+\alpha+\beta\frac{\sigma_{ss}}{f_{ck}}+\gamma\right] \tag{18}$$

This equation shows that the axial capacity increases with the self-stress and the constraint effect of the steel tube.

The second limit state of CFRP-SSCFST is CFRP sheet rupturing. The axial capacity of the CFRP-SSCFST can be expressed as:

$$N_{u2} = A_c\sigma_l + A_s\sigma_{sl} \tag{19}$$

Substituting Eqs. (2) (4) (10) (11) into Eq. (19) gives axial capacity as:

$$N_{u2} = A_c f_{ck}(1+3\xi_s\frac{\sigma_{st}}{f_y}+6\frac{\sigma_{ss}}{f_{ck}}+2\xi_f-\xi_s) \tag{20}$$

where $\xi_f = \dfrac{A_f f_f}{A_c f_{ck}}$

ξ_f is defined as the coefficient of the constraint effect caused by the CFRP sheet. The circumferential tensile stress of the steel tube σ_{st} will be the yield stress f_y and the circumferential tensile stress of the CFRP σ_{ft} will be the ultimate stress f_f when the steel tube yields and CFRP ruptures. Therefore, the axial capacity can be rewritten as:

$$N_{u2} = A_c f_{ck}(1+2\xi_s+6\frac{\sigma_{ss}}{f_{ck}}+2\xi_f) \tag{21}$$

This equation the axial capacity increases with the self-stress and the constraint effects of the CFRP and the steel tube.

Example

An example is employed to verify the effect of the self-stressing of the concrete and the reinforcement of the CFRP sheet. The thickness of the steel tube and the CFRP sheet are 1.5 mm and 0.17 mm, respectively. The yield strength of the steel tube and the ulitmate strength of the CFRP sheet are 350 MPa and 1500 MPa, respectively. The Young's modulus of the steel tube and CFRP sheet are 206 GPa and 230 GPa, respectively. The initial self-stress is 4.5 MPa. The diameter of the concrete core is 124 mm. The Poisson's ratio is 0.3 and the compressive strength of the concrete is 36.85 MPa.

The second limit state is the failure mode of the CFRP-SSCFST structures. The axial capacity is 1378 kN. It is 1052 kN when the self-stressing of the concrete is not considered and it is 1180 kN when the constraint of the CFRP sheet is not considered. The calculation results showed that the initial self-stress improves axial capacity of the SSCFST by about 30%; the CFRP reinforcement improves axial capacity by about 15%.

Conclusions

In this study, an analytical solution is presented to calculate the axial capacity of the SSCFST wrapped with CFRP sheets. The critical state of the steel tube was analyzed using the maximum shear stress theory. Two limit states of the axial capacity, including steel tube bucking and CFRP sheet rupturing are considered in the analysis. The analytical results of an example showed that the initial self-stress improved axial capacity of the SSCFST by about 30% and the CFRP reinforcement improved axial capacity by about 15%. The axial capacity increases with the initial self-stress and the constraint effect of the steel tube when failure results from bucking of the steel tube. The axial capacity increases with the initial self-stress and the constraint effect of the steel tube and the CFRP sheets when failure results from rupturing of the CFRP sheets and bucking of the steel tube as well.

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